DOE/FE-0398

OHIO POWER COMPANY

TIDD PFBC DEMONSTRATION PROJECT

PROJECT PERFORMANCE SUMMARY
CLEAN COAL TECHNOLOGY DEMONSTRATION PROGRAM

JUNE 1999

Ohio Power Company

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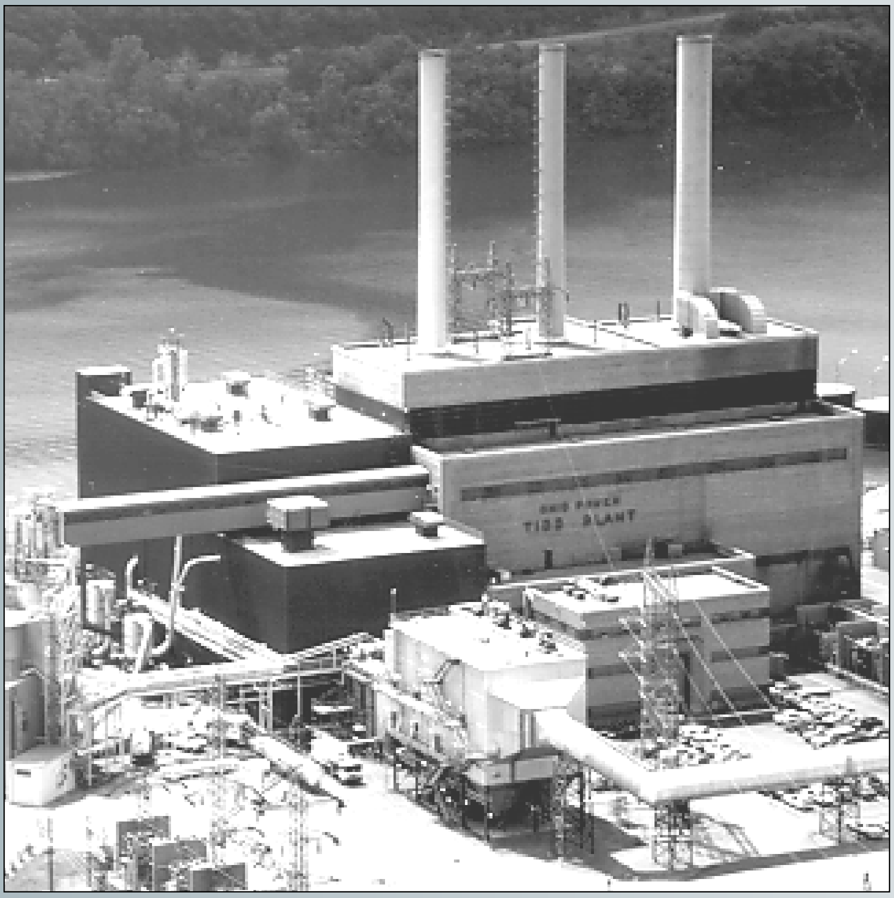
Tidd PFBC Demonstration Project



Project Performance Summary
Clean Coal Technology Demonstration Program

Advanced Electric Power Generation

OVERVIEW

The Tidd demonstration advanced PFBC technology to the threshold of commercialization and proved compatibility of PFBC with the energy and environmental demands of the 21st century.

The pressurized fluidized-bed combustion (PFBC) project at the Ohio Power Company Tidd plant represented the first large-scale operational demonstration of PFBC technology in the United States. Operation of the 70 MWe PFBC unit over a four-year period succeeded in establishing the commercial viability of PFBC technology, while developing and optimizing plant systems. The technology demonstrated the sound environmental and operational performance, and the economic and high-efficiency performance potential required for power generation in the 21st century.

The project is part of the U.S. Department of Energy's Clean Coal Technology Demonstration Program (CCTDP) established to address energy and environmental concerns related to coal use. Cost-shared partnerships with industry were sought through five national solicitations to accelerate commercialization of the most advanced coal-based power generation and pollution control technologies. The CCTDP, valued at nearly $6 billion, has leveraged federal funding twofold through the resultant partnerships encompassing utilities, technology developers, state governments, and research organizations. This project was one of 17 selected in July 1986 from 51 proposals submitted in response to the Program's first solicitation.

The Tidd demonstration fully assessed the potential of PFBC "bubbling-bed" technology through (1) evaluation of each subsystem, with implementation of design modifications and refinements as required; (2) parametric testing to understand the effects of key factors on performance; and (3) long-term testing to establish operational, environmental, and economic performance. Knowledge and experience gained in this critical development step, and the resultant comprehensive database, have positioned PFBC technology for commercial deployment.

High sulfur-capture efficiency resulted from the effective mixing and relatively lengthy gas residence times afforded by the pressurized fluidized-bed system. Calcium to sulfur molar ratios (Ca/S) as low as 1.14 achieved SO_2 reductions of 90 percent at full load conditions using high-sulfur coal. NO_x emissions ranged from 0.15 to 0.33 lb/10^6 Btu as a result of the low bed temperatures (maximum 1580 ^oF) and essentially isothermal fluid-bed conditions. Particulate emissions averaged less than 0.02 lb/10^6 Btu. Combustion efficiency exceeded 99 percent.

Tests over the four-year period proved the durability of the in-bed tube bundle characteristic of "bubbling-bed" systems, as well as gas turbine survivability with only cyclone particulate control. Economic analyses show PFBC costs compare favorably to other advanced coal-based power generation systems.

The Project

The Tidd PFBC demonstration project stemmed from American Electric Power Company (AEP) and Ohio Coal Development Office interest in finding a way to use indigenous high-sulfur coal resources to meet projected growth in electricity demand. AEP wanted a technology that could not only use indigenous coals but increase capacity at existing sites with minimum footprint and maximum use of existing equipment. AEP also wanted to capitalize on the experience of its plant personnel by selecting a technology where training and operation of conventional coal plants could be applied. PFBC met all these needs.

AEP entered into the project with the intent of fully evaluating PFBC performance characteristics on a system by system basis, modifying subsystems as necessary, optimizing overall system performance, and determining whether that performance was compatible with U.S. utility operations and future needs. Specific technical objectives of the project were to: (1) prove survivability of the in-bed tube bundle and gas turbine, (2) achieve greater than 90 percent sulfur capture at calcium-to-sulfur (Ca/S) molar ratios less than 2.0 and NO_x emissions less than 0.25 lb/10^6 Btu, (3) investigate commercial applications of PFBC ash, (4) demonstrate overall system reliability and availability consistent with commercialization, and (5) prove economic competitiveness with pulverized coal-fired plants with flue gas desulfurization and other advanced coal-based systems.

All objectives were met or exceeded in four years of testing at the Tidd 70 MWe demonstration facility located in Brilliant, Ohio. The original plan called for three years of testing, but problems with the prototype gas turbine, unrelated to the PFBC application, resulted in unanticipated and lengthy downtime. To ensure full evaluation of PFBC performance potential, the project was extended for an additional year. The demonstration plant was shut down in March 1995 upon completion of the planned tests.

The Tidd Plant ran strictly as a demonstration unit. It did not include redundancies and used the existing 1950s vintage steam plant, without reheat. Therefore, availability and efficiency values are not reflective of a commercial configuration. The final technical reports thoroughly assess the performance of each subsystem and the associated design modifications and refinements. This report focuses only on significant findings.

Project Sponsor

The Ohio Power Company (a wholly owned subsidiary of American Electric Power Company, Inc.)

Additional Team Members

American Electric Power Service Corporation — designer, constructor, and manager

The Babcock & Wilcox Company — technology supplier

Ohio Coal Development Office — cofunder

Location

Brilliant, Jefferson County, Ohio (Ohio Power Company's Tidd Plant, Unit No. 1)

Technology

The Babcock & Wilcox Company's pressurized fluidized-bed combustion system (under license from ABB Carbon)

Plant Capacity

70 MWe

Coal

Pittsburgh # 8, Ohio 6A, and Peabody Anker, 2–4% sulfur

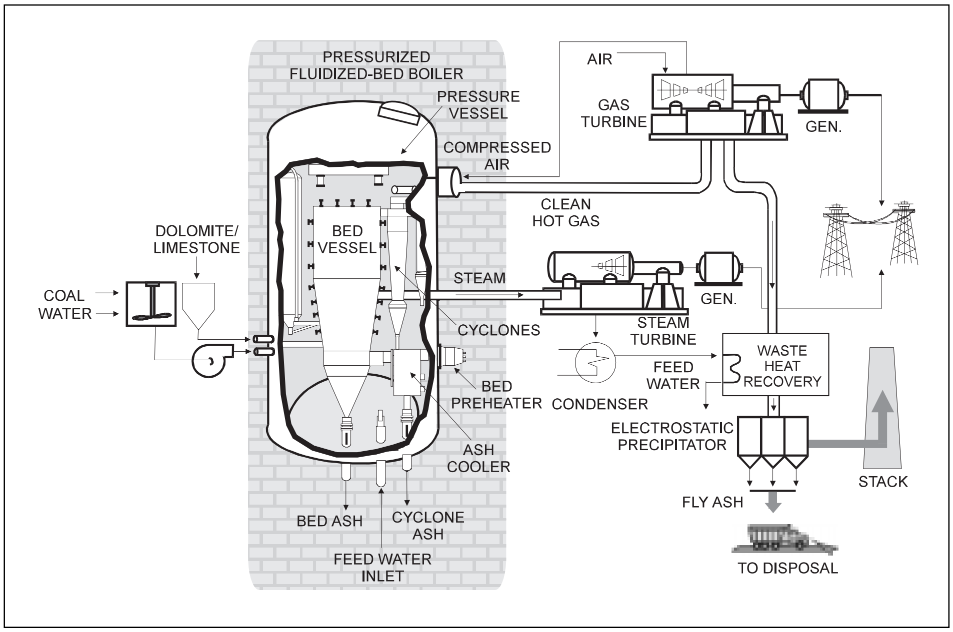
Demonstration Duration

February 1991–March 1995.

Project Funding

Total project cost	$189,886,339	100%
DOE	66,956,993	35%
Participant	122,929,346	65%

THE TECHNOLOGY



The PFBC technology demonstrated at Tidd uses a bubbling fluidized-bed combustion process operating at 12 atmospheres (175 psi). Bubbling-beds use the minimum air velocity necessary to suspend the bed particles in a highly turbulent state, typically 3–4 feet per second. For comparison, circulating fluidized-beds, the other fluidized-bed option, operate at higher fluidizing velocities (6–8 feet per second) to entrain and transport the bed material.

Low fluidizing velocities in bubbling-beds permit use of in-bed tube bundles, which provide highly effective transfer of bed heat, to generate steam. Submerged tubes attain high rates of heat transfer due to intimate moving contact of hot bed particles with the tubes. This results in overall heat transfer rates 4–5 times greater than is possible with conventional furnace gas/tube heat transfer and reduces the amount of tubing required for a given heat absorption. Furthermore, PFBC permits tight tube spacing and deep beds because the resultant incremental pressure increase is easily accommodated by the gas turbine compressor, which is designed to sustain high vessel pressure. This allows design of a highly compact boiler with a small footprint.

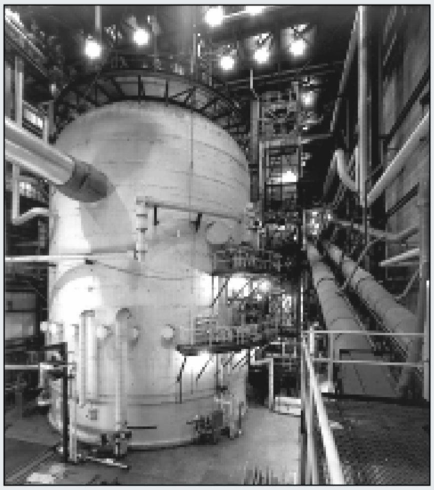
The deep, turbulent fluidized-bed produces excellent mixing and high residence times for the constituents. Fuel represents only about one percent of the bed material, with the balance being sorbent, reacted sorbent, and ash. This results in very high combustion efficiency at relatively low temperature (1580 ^{o}F), isothermal bed conditions, high sorbent utilization, and tolerance for a wide range of fuels. The low temperature, isothermal bed conditions mitigate NO_x formation, and high residence times and intimate constituent contact effect high sulfur capture efficiency. High bed pressure not only contributes to combustor performance, but also provides sufficient excess energy to drive a gas turbine, enabling combined-cycle operation and the attendant efficiency benefits.

Primary and secondary cyclones remove 98 percent of the particulates leaving the fluidized-bed. (At Tidd, provision was also made for a slipstream to test an advanced candle filtration system.) Steam capacity is controlled by adjusting bed level, which alters the amount of bed material in contact with the in-bed tubes. Two reinjection vessels adjacent to the bed vessel (boiler) are used to control bed level. The boiler, cyclones, and reinjection vessels are encapsulated in a pressure vessel 45 feet in diameter and 70 feet tall. The gas turbine compressor supplies pressurized combustion air to fluidize the bed material. Piston pumps supply fuel as a coal-water paste (75 percent coal) and a pneumatic system injects sorbent into the boiler. For the Tidd application, cleaned gases were expanded through a 15 MWe gas turbine and heat from the turbine exhaust and in-bed tube bundle generated steam to drive an existing 55 MWe steam turbine.

Demonstration Results

- Sorbent size had the greatest effect on SO_2 removal efficiency and the stabilization and heat transfer characteristics of the fluidized-bed.
- Tests showed that SO_2 removal efficiencies of 90 and 95 percent were achievable at full load and a temperature of 1,580 ^oF with Ca/S molar ratios of 1.14 and 1.5, respectively.
- NO_x emissions ranged from 0.15-0.33 lb/10^6 Btu, but were typically around 0.20 lb/10^6 Btu during the test period.
- CO emissions remained below 0.01 lb/10^6 Btu.
- Particulate emissions were less than 0.02 lb/10^6 Btu.
- Combustion efficiency ranged from an average 99.3 percent at low bed levels to an average 99.5 percent at moderate to full bed height levels.
- Heat rate was 10,280 Btu/kWh based on higher heating value of the fuel and gross electrical output, or 33.2 percent efficiency. (Contributing to the low values were use of a 1950s vintage steam generator without reheat, less than optimum performance of the prototype gas turbine, no attempt to optimize heat recovery, and the small scale of the demonstration unit.)
- An Advanced Particulate Filter (APF) using a silicon carbide candle filter array on a flue gas slip stream achieved 99.99 percent filtration efficiency on a mass basis.
- The PFBC boiler demonstrated commercial readiness, as evidenced by lack of erosion in the in-bed tube bundle and sustained operation at targeted performance levels.
- The ASEA Stal GT-35P gas turbine proved capable of operating commercially in a PFBC flue gas environment, but failed to meet performance requirements for reasons unrelated to the PFBC technology.

Worker's ready to unload the prefabricated pressure vessel



Pressure vessel is shown fully installed with insulation on exposed surface

Operational Performance

The Tidd unit logged 11,444 hours of coal-fired operation over a four year period while 95 separate performance tests were conducted. Performance tests were conducted at steady-state conditions over periods of 4–12 hours. Process data was averaged during the test period, and materials sampling (coal, coal-water paste, sorbent, bed and cyclone ash) took place before, during, and after the test period, as appropriate. Process and chemical analysis data were used to calculate coal-water paste flow, flue gas flow to the high pressure turbine, excess air, sulfur retention, Ca/S molar ratio, NO_x emissions, and combustion efficiency. Mass and heat balance calculations validated the accuracy of the performance tests. Test variables included coal and sorbent type, coal-water paste composition, sorbent size and size consist (size distribution), sorbent injection configuration, bed level, bed temperature, firing rate, and excess oxygen.

The design coal for the Tidd plant was Pittsburgh #8 coal from M&M Coal Company's Betsy Mine. Other Pittsburgh #8 coals tested came from the Minnehaha and Consol Mahoning Valley Mines. Tests were also conducted on Ohio 6A and Peabody Anker coals. The design sorbent was Plum Run Greenfield dolomite. Two other dolomites and two limestone sorbents, discussed later, were evaluated. *Table 1* provides the characteristics of the design feedstocks.

TABLE 1: DESIGN COAL & SORBENT ANALYSES

Coal Company Mine and Seam	M&M Coal Company Betsy Mine Pittsburgh #8
Sample Number	C-410419
Sample Date	October 13, 1994
Proximate Ananlyses	
% Total Moisture	4.52
% Ash (D/B)	11.64
% Sulfur (D/B)	3.20
HHV, Btu/lbm (D/B)	13,048
SO_2, lbm/10^6Btu (D/B)	4.91
Ultimate Analyses	
% Carbon (D/B)	70.91
% Hydrogen (D/B)	4.40
% Nitrogen (D/B)	1.39
% Chlorine (D/B)	0.02
% Oxygen (D/B)	8.26
Typical Sorbent Analyses	
Company Name	Davon Inc. Plum Run Division
Geological formation	Greenfield
Sorbent Type	Dolomite
Sample Date	3/07/95
Constituents Analyses	
% Total Moisture	0.04
% $CaCO_3$ (D/B)	52.44
% $MgCO_3$ (D/B)	43.95
* D/B is dry basis	

PFBC COMBUSTOR

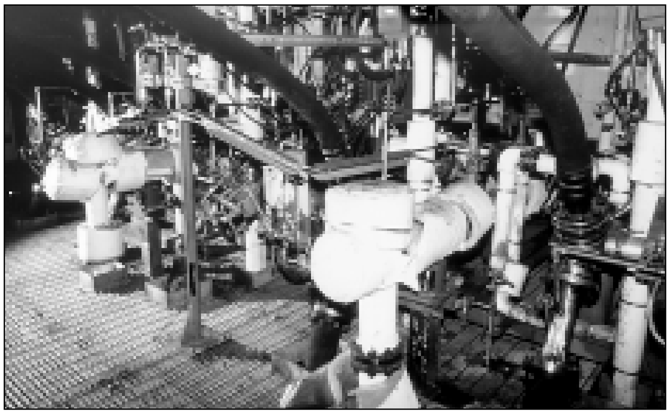
A number of PFBC combustor systems demanded particular attention in order to sustain operation of the unit and meet performance objectives. Every effort was made to determine underlying causes of disruptive occurrences or performance shortfalls and to develop systemic solutions.

Post-bed Combustion— In the early stages of operation, localized combustion was found to occur beyond the fluidized-bed. Such combustion threatened to exceed the gas turbine inlet design temperature unless bed temperatures were below 1540 °F. Post-bed combustion was evidenced by combustion of volatiles in the freeboard region and combustion of fine char in the primary cyclone dip leg. The cause was attributed to highly localized release of coal volatiles and fine char near the fuel nozzle discharge points. The high concentration of the volatiles and the presence of steam at the coal nozzles impeded combustion. "Plumes" of unburned volatiles, steam, fine char, and combustion gases formed and permeated through the bed and into the freeboard where excess oxygen ignited the mixture. High localized temperatures in the freeboard prompted combustion in the primary cyclone dip legs, causing plugging.

To reduce the concentration of plume constituents, "skateboards" were installed above the fuel nozzles and more fluidizing air was apportioned to the nozzles to aid dispersion. The volume of air used to break up the coal-water paste (splitting air) in the two-stage fuel nozzle was reduced to increase the size of the paste lumps. A recycle loop was added to the coal crusher to produce more fines and enable less water content, which increased paste cohesiveness. The increased cohesiveness reduced fines formation at the fuel nozzles and lower water content reduced localized steam formation at the nozzle. In addition to these changes, a freeboard gas mixing system was installed. With these modifications, post-bed combustion ceased to be a problem.

Fuel System— Adding a coal crusher recycle loop for more fines production to address post-bed combustion also eliminated persistent fuel line plugging. The fines reduced the flow resistance of the coal-water paste and provided a consistent, low moisture, cohesive fuel compatible with the combustor. However, consistent production of the desired amount of fines proved to be difficult with other than the Pittsburgh #8 design coal, indicating the need for crusher redundancy in a commercial plant.

Ash Removal System— Plugging of primary and secondary ash removal lines also was a frequent occurrence in the early stages of testing. The causes included air leakage,



Shown here are sorbent (white) and fuel injectors (hose junctures) located on the same boiler level

insufficient transport capacity, and use of parallel transport lines. Air leakage into the transport lines located in the pressure vessel occured at poorly sealed flanges and connections because of the increased pressure differential as ash/gas proceeded down the line. Air leakage displaced transport gas, reducing velocity upstream of the leakage and initiating ash deposition. This eventually led to plugging as ash accumulated. Insufficient gas velocities in the lines, as was found in the secondary system under normal conditions, limited capacity. Use of parallel transport lines from a common collection manifold, as used at Tidd, precluded a natural clearing mechanism. If one of the seven parallel lines experienced blockage, it was subject to only a fraction of the full system pressure drop.

The secondary ash removal system underwent major modifications. These included use of continuous welded construction to eliminate connections, avoidance of sharp bends, elimination of parallel transport, an increase in gas velocity, and placement of the lines outside of the pressure vessel with access valves to facilitate cleaning. Subsequent to these modifications, no further problems were experienced with the secondary ash removal system. The cost of a similar modification to the primary system on the demonstration unit was prohibitive, but would be incorporated in a commercial design. Primary ash removal plugging was avoided through frequent gasket changes to the primary system flanges and operational adjustments.

Sorbent System— Sorbent preparation required unacceptably high maintenance throughout the four year test program. The affected components included the impact/dryer mill, cyclone separator, and vibrating screen for establishing top size. Hardening of components in the impact/dryer mill and installing tile lining in the cyclone resolved wear problems for these components. The vibrating screen, originally designed for 12-mesh top size, was initially replaced with a coarser 6-mesh screen to address wear and blinding problems. In the fourth year, a modified 12-mesh screen was installed. In general, the system suffered from marginal capacity and design limitations. However, sufficient data was collected for design of an acceptable commercial system.

Sorbent delivery shortcomings were resolved over the course of the demonstration. Components modified included the lockhoppers, variable speed rotary star feeders at the base of the lockhoppers, and the distribution system. The lockhoppers underwent valve modifications, additional power and a lower speed capability was applied to the star feeders, and ceramic lining was incorporated throughout the distribution system.

Also, configuration changes were made to the sorbent distribution piping and injection points. Originally, two lockhoppers alternately fed a single transport line which bifurcated just prior to the pressure vessel. The two injection points, on the same level as the fuel ports and between them, extended into the boiler some distance. Extension of the sorbent injectors into the boiler was found to cause clinker formation on the in-bed tubes and the injection point was moved back to the boiler wall. To improve sorbent distribution, the two injection lines were bifurcated again to increase the sorbent injection ports to four. This alone improved sorbent utilization by 12–15 percent at 115 inches bed level (no definitive improvements were noted at the full bed level of 142 inches).

Bed Sintering— Bed sintering limited bed temperature through the first three years of testing. At bed temperatures in excess of about 1520 °F, the fluidized-bed would begin to deteriorate, as evidenced by decreasing bed density and tube bundle absorption, widely varying temperatures in the bed and evaporator outlet, and decreasing bed temperatures immediately above the sparge nozzles. Under these conditions, hollow egg-shaped sinters called “egg sinters” (½ to 2 inches in size) would form and eventually force shutdown of the system. Even at bed temperatures below 1500 °F, limestone sorbents induced bed deterioration and sintering.

Through separate research efforts, the mechanism for “egg sinter” formation was determined to be fusing of ash particles to agglomerated lumps of coal paste and subsequent burnout of the coal, leaving a hollow center. The calcium in the sorbent was found to flux the potassium-alumina-silicate clays resulting in lower melting point eutectics (lowest temperature at which the mixture solidifies). Smaller coal paste lumps were determined to be less prone to sintering because fusing of the coal ash was limited by available surface area. Magnesium in the sorbent raised the eutectic temperature and mitigated sinter formation.

Investigations into the sintering mechanism revealed that increasing fluidization velocity from 3 to 4 feet per second eliminated the problem. However, fluidization velocity was fixed at 3 feet per second for the Tidd unit due to gas turbine volumetric flow characteristics and bed plan area. The only avenue available for increasing fluidization velocity was to reduce bed particle size. Bed material was predominantly spent sorbent which tended to maintain the same size consist as the raw sorbent feed. Thus the first step to resolve the problem was to use finer sorbent.

On reducing the top size of dolomite sorbent from 6-mesh to 12-mesh, sintering ceased to be a problem and heat transfer in the bed improved as well. However, limestone (even limestone high in magnesium content) induced bed deterioration independent of size consist. Further testing indicated that bed deterioration was the precursor to sinter formation, contrary to initial thinking that sintering caused the bed deterioration.

Combustion Efficiency— Elimination of bed sintering opened the way for performance testing at the design temperature of 1580 °F and the pursuit of sorbent size optimization. At 1580 °F, combustion efficiency increased, reaching as high as 99.75 percent at full bed height. Combustion efficiency for bed heights of 110 inches to the full 142 inches averaged 99.5 percent, and for bed levels below 110 inches the average efficiency was 99.3 percent. In-bed heat absorption improved with the use of finer sorbent up to the expected level at 1540 °F, and beyond expected absorption by 5.5 percent at 1580 °F. This was significant because an early modification was made to meet absorption design rates by adding tubing and increasing bed height from 126 inches to 142 inches. The design temperature was lowered to 1540 °F as a protection against post-bed combustion occurrences, since resolved.

Boiler. Wear of boiler components was not a problem at Tidd. The in-bed tube bundle experienced some localized erosion as a result of a missing personnel access hatch seal. Two superheater tube leaks in the fourth year of operation were attributed to stress corrosion. Thinning on all four walls of the boiler was observed in the region five feet above the air sparge ducts and three feet below the top of the tube bundle. This was not considered significant from a commercial operation standpoint because the region is not critical to heat transfer, affording the option of protective shielding.

Unit availability increased steadily over the demonstration period, exceeding 54 percent in the fourth year. Total plant output reached 72 MWe, just short of the design output of 72.5 MWe.

Gas Turbine

Low-pressure Turbine/Compressor Blades— The prototype ASEA Stal GT-35P gas turbine was the leading cause of unit unavailability during the first three years of operation. Design problems were uncovered in the low-pressure turbine blades and low-pressure compressor stationary blades. Failures included cracks and one catastrophic event, which alone caused a 20-week downtime. The problems, however, were not attributable to operation in the PFBC plant. Some erosion was detected in the low-pressure turbine variable pitch inlet guide vanes. A design modification to correct the problem had already been developed, but, the extent of damage and length of demonstration did not warrant modification of the Tidd unit.

Air Leakage— Excessive air leakage in the prototype gas turbine also hampered testing. Only during low ambient air temperature conditions could the turbine deliver the required mass air flow for the firing rate needed to achieve the design temperature of 1580 °F. Summer conditions severely impacted performance not only because of high ambient air temperatures but because of high temperatures of the river water used in the compressor stage intercooler.

Environmental Performance

Sorbent Utilization— Optimizing sorbent utilization for SO_2 control became the focus of the fourth year of testing after resolution of the bed sintering problem. Sorbent size was determined to have the greatest impact on sorbent utilization. A series of tests were conducted with finer sorbent top sizes than could be produced from the on-site preparation system. Tests included designer sizes having a narrow size consist range and containing fewer fines. Results showed that the optimum particle size, as measured by degree of sulfation, was about 60-mesh, just over the directly elutriable size. Particles in the 20x60-mesh range were the most sulfated. Low sulfation of sorbent fines was noted and attributed to short residence times in the bed. This theory was supported by relatively low cyclone ash sulfation rates.

Use of 12-mesh top size was chosen for the sorbent. Operation with 20-mesh "designer" sorbents (prepared off-site) was feasible, but even these had sufficient fines to cause bed ash rat-holing in the lockhoppers, resulting in overheating of the lockhoppers and sparge ducts. The on-site sorbent preparation system was modified to produce 12-mesh top size and produced the sorbent for the balance of testing. For the Plum Run Greenfield dolomite design sorbent, on-site prepared product had a size consist of 38 percent between 18- and 60-mesh and 48 percent less than 60-mesh. Plum Run Greenfield designer sorbent had a size consist of 63 percent between 18- and 60-mesh and 25 percent less than 60-mesh.

The sorbent type also affected sorbent utilization. Three dolomites and two limestones were tested. Plum Run Greenfield dolomite appeared to be 10–15 percent more reactive than a National Lime Carey dolomite tested. A Mulzer Laurel dolomite appeared to be as reactive as the Plum Run Greenfield dolomite. National Lime Bucyrus 18-mesh designer limestone and National Lime Delaware 12-mesh limestone achieved sorbent utilization roughly comparable to the dolomites on a mass basis. Testing was limited due to early onset of bed deterioration with the limestone sorbents (cause unknown).

The best sorbent utilization results were obtained using Plum Run Greenfield 12-mesh designer dolomite. At 115 inches bed level and 1580 ^{o}F, 90 percent sulfur retention was achieved with a Ca/S molar ratio of 1.26. Using a correlation developed in previous PFBC pilot plant work (Grimethorpe correlation) and validated for the Tidd demonstration, the Ca/S molar ratio needed at full bed height and 1580 ^{o}F was calculated to be 1.14 for 90 percent sulfur removal and 1.5 for 95 percent removal. *Figure 1* shows sorbent utilization versus bed height for three Plum Run Greenfield (PRG) dolomite preparations.

SO_2 Emissions— Using the design baseline coal, SO_2 emissions at the 90 percent reduction level were approximately 0.5 lb/10^6 Btu and at the 95 percent reduction level were approximately 0.25 lb/10^6 Btu.

NO_x Emissions— NO_x emissions ranged from 0.15–0.33 lb/10^6 Btu over the course of testing, but were typically around 0.20 lb/10^6 Btu, as shown in *Figure 2*. Figure 2 shows NO_x emissions plotted against percent oxygen in the freeboard for all performance tests conducted during the fourth year. As expected, NO_x emissions increased with an increase in excess air. The impact of nitrogen in the coal on NO_x emissions was not investigated at Tidd because the three coals tested varied little in nitrogen content.

CO Emissions— Because of the high combustion efficiency, CO emissions were quite low, and were less than the design target of 0.01 lb/10^6 Btu.

Particulate Emissions— The primary and secondary cyclone system removed about 98 percent of the ash, and an electrostatic precipitator (ESP) controlled the balance of the ash emissions. Dust loadings of 498.7 lb/hr were measured at the ESP inlet and 14.6 lb/hr at the outlet, which equates to a 97.1 percent collection efficiency. Particulate emissions from the plant were consistently below 0.02 lb/10^6 Btu, and were well under the permitted level of 0.03 lb/10^6 Btu.

In parallel with the Tidd PFBC demonstration, there was a program to evaluate the design and operability of a commercial size Advanced Particulate Filter (APF) designed for hot gas cleanup. Westinghouse Science and Technology Center provided a candle filter-based system. The APF began initial operation in May 1992 and was commissioned in October 1992. The system operated during five separate test periods between October 1992 and March 1995, compiling a total of 5854 hours of coal-fire operation. The system was designed to remove virtually all entrained particles from one of the seven primary cyclones on the outlet of the PFBC combustor, making it a 10 MWe equivalent system.

Figure 1: Bed Height vs Ca/S Ratio

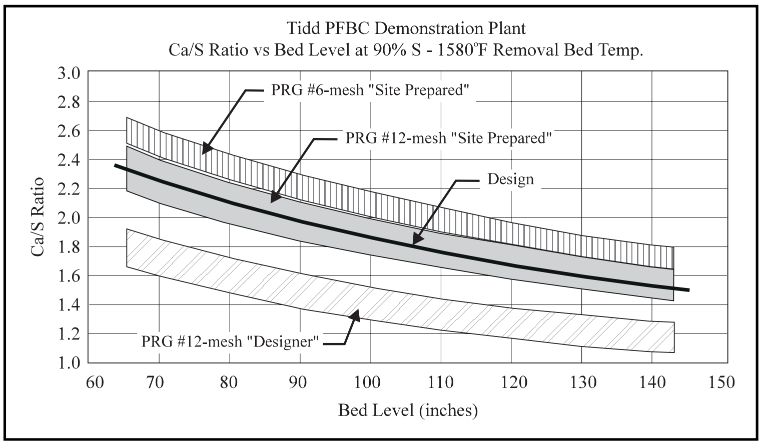
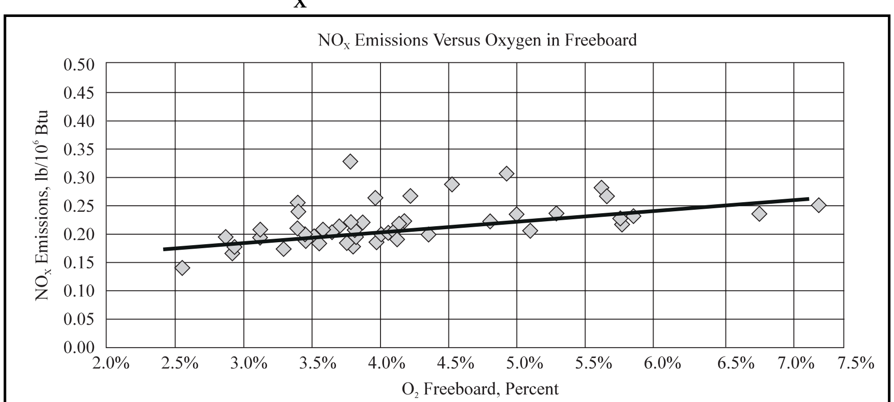


Figure 2: NO_X Emissions vs Oxygen in Freeboard



In the APF, ash collects on the outside surfaces of ceramic filter elements (candles), resulting in a gradual increase in resistance to overall flow. A high pressure air pulse periodically applied to the clean side of the candles dislodges the filter cake and reduces the resisitance to flow. The ash cake on the candles then falls to a conical discharge hopper where the ash is removed from the filter vessel, cooled by an ash screw cooler, and discharged into a lockhopper system.

The APF initially contained 384 filter elements, referred to as candles because of their long, cylindrical shape. Each candle was 4.92 feet long and had an outside diameter of 2.36 inches. The candles were made of two layers of clay-bonded, sintered silicon carbide. Alternate materials were tested during the latter part of the testing program.

In the initial testing, the APF saw the the same dust loading as a single secondary cyclone—600 ppmw, 3-micron mass mean particle size (MMPS). Problems with broken candles resulted from bridging of ash deposits between candles and support pipes and candles. A subsequent test had the inner rows of candles removed (total candles reduced to 288) and the primary cyclone detuned, increasing the dust loading to 3400 ppmw at a MMPS of 7-microns. Performance improved but the bridging persisted. A final test had the primary cyclone removed from service and three other candle types installed, increasing the dust loading to 20,000 ppmw. No bridging occured and the system performed well despite failure of almost all of one new filter type and partial failure of another.

In summary, the tests showed that: (1) the basic design of the candle-based APF was structurally adequate; (2) the clay bonded silicon carbide candles exhibited a 50 percent loss of strength after 1000 to 2000 hours of operation, but stabilized and maintained adequate strength upon further exposure; (3) nearly all candle breakage was attributable to ash bridging, which was strongly affected by the size and temperature of the ash entering the filter; (4) ash must be prevented from entering the candle to avoid blinding and cracking; (5) design of the hot gas piping was critical because of the high-temperature, corrosive, and abrasive flue gas; (6) the ash removal system design was critical because ash buildup can cause candle breakage; (7) a failsafe mechanism proved effective in preventing flue gas bypass upon filter breakage; and (8) particulate removal efficiency of the APF was 99.99 percent.

Hazardous Air Pollutant (HAP) Testing— Comprehensive HAP testing was conducted at Tidd and presented in a Topical Report referenced in this report. Analyses address trace elements, minor and major elements, anions, volatile organic compounds, dioxin/furan compounds, ammonia, cyanide, formaldehyde, and semivolatile organic compounds.

Removal efficiencies for non-volatile metals were generally greater than 95 percent across the ESP. Less than 10 percent removal was observed for volatile species such as chloride, fluoride, and mercury.

Removal efficiencies for most non-volatile metals was greater than 99.5 percent across the APF. Removals of less than 30 percent were measured for mercury, selenium, chloride, and fluoride. Approximately 40 percent removal of SO_2 was measured across the APF system, as well as some removal for ammonia (25 percent), cyanide (69 percent), and formaldehyde (94 percent).

Solid Waste Utilization— The Ohio Coal Development Office sponsored a series of tests to evaluate commercial uses of Tidd PFBC ash. Results showed the ash to be effective in: (1) stabilizing soil when mixed with the soil; (2) serving as a stand-alone construction material in applications such as feedlot floors and highway embankment and road-bed stabilization; and (3) enhancing soil quality in surface mine reclamation and agricultural applications without compromising the environment.

Economic Performance

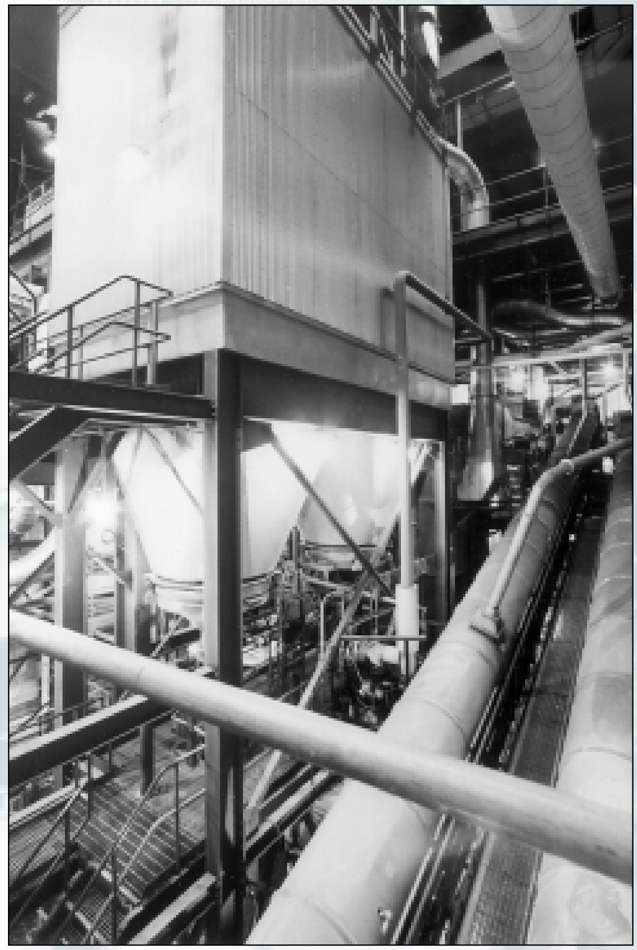
The focal point of the Tidd demonstration was to develop the technology for scale-up to a commercial size unit larger than 300 MWe. Commercial design at this scale incorporates ABB Carbon's P800 PFBC combustor and the ASEA Stal GT-140 P gas turbine. Originally, the P800 had a projected nominal 350 MWe output for a greenfield application. Estimates conducted later, however, assumed a larger boiler (to fully utilize turbine output at lower ambient temperatures) and a nominal 380 MWe output, with 70 MWe coming from the gas turbine.

In 1994, AEP conducted an extensive cost-estimating effort for a repowering application integrated into a supercritical steam cycle and having 370 MWe net output (under Spring conditions). The full-load net unit heat rate was calculated at 8874 Btu/kWhr under Spring conditions. Estimates determined the overnight capital cost to be $365 million (1994 $), which included a significant amount of balance of plant work. AEP also referenced a 1994 cost estimate performed by ABB Carbon for a greenfield P800 PFBC facility. That effort resulted in an estimate of $436 million (1994 $) as the overnight capital cost for a 380 MWe unit using a subcritical steam cycle. The 1994 cost estimates performed for the repowering and greenfield applications represented first-of-a-kind commercial P800 PFBC islands, as opposed to estimates prepared after several plants have been constructed (Nth plant estimates).

In preparing the 370 MWe repowering evaluation, AEP also estimated construction time and operation and maintenance costs. Construction was projected to take 42–48 months. Estimates for annual operation and maintenance costs were $4.4 million and $9.5 million, respectively. These costs included all fixed and variable operation costs except for the cost of raw sorbent and coal, and the cost of ash disposal. Maintenance costs reflected all fixed and variable maintenance costs for the repowered facility except for the major periodic gas turbine and boiler refurbishment costs identified in *Table 2*.

A recent cost estimate was performed on Japan's 360 MWe (net output) Karita Plant scheduled to commence operation in 1999. The Karita plant represents an Nth plant. The estimate included the P800 PFBC combustor, ASEA Stal GT-140 gas turbine operating in a combined cycle mode, limestone or dolomite sorbent, cyclones for particulate control upstream of the gas turbine, and an ESP downstream of the turbine. *Table 3* shows the capital cost using "EPRI TAG 1993" assumptions and performance characteristics established by ABB Carbon.

During the demonstration, AEP conducted a comparative cost analysis between PFBC, a pulverized coal-fired plant with flue gas desulfurization, and other advanced, but mature, coal-based technologies, and concluded that PFBC was the lowest-cost option on a cost-of-electricity basis.



Sorbent silos with coal and sorbent converyors to the right.

Table 2. Major Refurbishment Items and Costs

Major Maintenance Item	Frequency	Cost(1994 $)
Refurbish GT Turbine Blading	Every 3-years	$1.5 million
Refurbish GT Compressor Blading	Every 12-years	$1.5 million
Replace boiler tube bundle	Every 10-years	$15.0million

Table 3. Nth Plant Characteristics

Net Power Output	360 MWe
Plant Efficiency, HHV	42.0%
SO_2 Emissions	0.16 lb/10^6 Btu
NO_x Emissions	0.10 lb/10^6 Btu
Particulates	0.01 lb/10^6 Btu
Total Plant Cost, 1997 $	$1,263/kW

Commercial Applications

Clean coal technologies in general, and PFBC technology in particular, offer an important opportunity for sustained economic development, both domestically and internationally. However, as with most technologies in the capital intensive power industry, these new technologies require 20 to 25 years from their initial development stages to the point where the technology risk has been sufficiently reduced for power generation companies to assume the risk of commercial deployment. Most of the development work required for the PFBC bubbling-bed technology to reach this phase has been completed. The successful operation of the Tidd PFBC Demonstration Project has established the viability of the process, while developing and optimizing plant systems. Successful continued operation of PFBC plants throughout the world — at places such as Vartan in Sweden, Escatron in Spain, and Wakamatsu in Japan — continue to demonstrate the viability of PFBC technology. Growing acceptance of PFBC is reflected in the fact that two more PFBC bubbling-bed units are scheduled to come on-line in 1999—a 360 MWe unit in Karita, Japan (ABB Carbon technology), and a 74 MWe/120 MWth unit in Cottbus, Germany (ABB Carbon technology). *Table 4* lists PFBC Commercial scale plants.

Power generation companies are concerned about future competition as well as the availability of primary energy sources for power generation. Virtually all integrated resource plans for the next ten to fifteen years rely on the addition of simple-cycle or combined-cycle natural gas-fired combustion turbine systems to meet near-term growth needs, satisfy peak demands, and achieve environmental compliance at least cost. However, coal-fired systems are expected to provide a significant portion of future additions to base-load power generation.

It is widely predicted that some time after the year 2000, domestic electricity demand will catch up to available generating capacity and, as a result, new power plant construction will have to increase. In addition, a large portion of existing generating capacity will be reaching the end of its useful life and will need to be replaced. This includes nuclear plant retirements, which currently provide about 19 percent of electric power generation. Restructuring of the utility sector, already underway in several states, may accelerate nuclear plant retirements. Taken together, these factors should result in a significant market for new and repowered generation facilities. PFBC operational, environmental, and economic performance should place it in a strong position to capture a significant share of the developing market.

Table 4: PFBC Commercial Scale Plants

Plant	Type	Size	Location	Vendor	Status
Värtan	Bubbling Bed (two units)	135 MWe +225 MWth	Sweden	ABB Carbon	Operational 1989
Escatron	Bubbling Bed	70 MWe	Spain	ABB Carbon	Operational 1990
Tidd	Bubbling Bed	70 MWe	U.S.	B&W under license from ABB Carbon	Testing Completed Shut Down
Wakamatsu	Bubbling Bed	70 MWe	Japan	IHI under license from ABB Carbon	Operational 1993
Karita	Bubbling Bed	360 MWe	Japan	IHI under license from ABB Carbon	Operational 1999
Cottbus	Bubbling Bed	74 MWe +120 MWth	Germany	ABB Carbon	Operational 1999

Contacts

Mario Marrocco
American Electric Power Service Corporation
1 Riverside Plaza
Columbus, Ohio 43215
(614) 223-2460

George Lynch, DOE/HQ
(301) 903-9434
george.lynch@hq.doe.gov

Donald W. Geiling, FETC
(304) 285-4784
dgeiling@fetc.doe.gov

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U.S. Department of Energy

Assistant Secretary for Fossil Energy

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